Urban and rural measurements of atmospheric potential gradient

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Abstract

Atmospheric potential gradient was measured at three sites within the Bristol area of the UK between 19th May and 24th June 2016. Two sites were on rooftops within the city of Bristol, 800 m apart from each other, while the third was in a rural location 17 km to the south. Potential gradient measurements at the two rooftop urban sites showed great temporal similarity, implying that a rooftop measurement may be assumed to represent the local urban area. Frequency domain analysis indicated a half-day cycle in the urban sites that was not observed in the rural site, consistent with other studies showing the effect of traffic aerosol on potential gradient measurements. The correlation between the two urban sites was not affected by an increase in aerosol concentration. Removal of data during rainfall, as well as one hour before and after rain removed some of the larger changes in potential gradient typical of disturbed weather. However, large changes of potential gradient still existed, showing that rainfall alone should not be relied upon as an indicator of a non-fair weather potential gradient.

Keywords

Atmospheric electricity, aerosol, urban environment, disturbed weather

1. Introduction

The Atmospheric Potential Gradient (PG) is the vertical electric field present in the atmosphere, with positive values indicating a downward pointing field. The PG is an atmospheric measurement that has been recorded through recent history and is now becoming more common as modern field mill designs enable continuous robust measurements in many different environments. These measurements have been used to infer presence and physical characteristics of aerosols [1, 2], and the passage of smoke in historical data [3, 4]. PG has been used to measure meteorological phenomena and the passage of charged plumes overhead [5, 6]. Current research on the electrosensitivity of insects and spiders require an understanding of the local PG to better understand animal behaviour [7, 8].

The global background PG is a consequence of the Earth's electrical circuit which is generated by thunderstorm activity throughout the globe [9, 10]; thunderstorms transfer charge from the ground to the ionosphere, which is maintained at a high potential (~2.4×10^5 V) [11]. This charge transfers back to ground through an atmosphere that is weakly conducting due to the presence of atmospheric ions created by cosmic and solar rays and (closer to the surface) by ground based radiation. Whilst the vertical current density flowing between the ionosphere and surface is small, of order 10^{-12} Am^{-2} [11], this current produces an appreciable potential gradient of ~100 Vm^{-1} near the surface due to its flow through the extremely low conductivity air. The global background PG has a 24 hour cycle, caused by the daily variation of thunderstorm and shower cloud activity throughout the globe and therefore ionospheric potential [9]. This cycle was found by averaging the diurnal cycle of PG measured on the research ship Carnegie in a series of cruises between 1909 and 1929 [12]. This variation is not usually seen in urban fields as local sources can mask it.

On a regional scale, charged rain clouds and precipitation cause large fluctuations to the global background PG to such an extent that analysis of PG with a view to global processes is often constrained to fair weather measurements, though the definition of fair weather can vary it is typically described by a clear sky, low wind speeds and no precipitation [13]. Locally, sources of space charge (splashing water, power lines, combustion sources) can cause changes in PG through Coulomb fields [14-16], and sources of aerosol can cause a reduction in atmospheric conductivity locally through attachment of ions to aerosols, and hence increase the local field as a consequence of Ohm’s law [3, 17].

Within an urban environment, there is an increased aerosol content which can affect levels of PG [18], and therefore it is important to be able to discern the effects of local sources on the PG time series recorded. Analysis from two measurement positions in a city will allow the extent of local PG disruption to be viewed, and a comparison to a third rural site will give an indication of how the city environment can disrupt the field. The early results presented here seek to prove the value of measuring PG in a city, and will help to interpret further results from urban sites.

1.1 Global factors affecting atmospheric PG

The amount of ionisation that occurs in the atmosphere is dependent on the amount and penetration of galactic cosmic rays. As the solar-magnetic and geomagnetic fields give a level of shielding to cosmic rays, there is an effect of the Sun’s activity on the Earth’s electric field due to decreased shielding of cosmic rays. This is shown by an 11-year cycle, corresponding to solar activity, in the global electric circuit [19]. In addition, cosmic ray events and solar events have also been shown to affect the Earth’s circuit [20]. Thunderstorms are the main driver of the atmospheric electric field, changes in potential across a thundercloud caused by internal processes cause electrical breakdown across clouds or towards the ground. Ground strikes from thunderstorms, breakdown events and currents above and below clouds are what cause charge to be transferred to the ionosphere. The global electrical circuit is completed by the air-Earth current carried by charge carriers in the atmosphere transferring charge back to ground and maintaining the ionospheric potential [19].

1.2 Regional factors affecting atmospheric PG

Regionally, the global electric field is affected by the local weather; thunderstorms are the most dramatic of examples, but rainclouds and fog also affect the value of PG measured at the ground [22]. Fog has a large effect on the local PG; Piper and Bennett [5] demonstrate a change in PG during a fog and mist event, with an increase in PG when fog begins, and an increase in variability as the fog begins to dissipate.

Many measurements of atmospheric PG around the globe, including measurements presented here from Bristol, are now being collected as part of the Global Co-ordination of Atmospheric Electricity Measurements (GloCAEM; https://glocaem.wordpress.com/). This will better enable regional differences and the global nature of the atmospheric electric circuit to be explored.

1.3 Local sources of space charge affecting atmospheric PG

Local sources of PG can cause large changes in atmospheric PG over a short distance. Atmospheric ions produced by high voltage power lines can remain aloft in the air, attaching to aerosols, and cause large perturbations to the PG when compared with measurements made upwind [15, 23]. Splashing water can create space charge [24, 14]. Near a lake in Portugal, PG measurements were used to elucidate space charge caused by breaking water, as well as the convective effect of the so-called 'lake breeze' which acted to remove aerosol and transport freshly created ions over the measurement sites [25]. Traffic can produce highly charged particles due to combustion processes in the engine [16, 26].

1.4 *Local effects of aerosol on atmospheric PG*

Successful attempts have been made to infer the presence of pollutants from historic PG measurements. Harrison [4] used atmospheric conductivity and PG measurements to infer smoke levels; assuming that increases in PG were caused by decreased atmospheric conductivity due to attachment of ions to smoke particles, testing the method when smoke concentrations were known. The technique proved effective in estimating smoke concentrations from London at Kew. Using a similar approach, levels of pollution from Glasgow and the surrounding area were determined from measurements of PG undertaken at multiple points in Scotland by Lord Kelvin and by applying plume dynamics [3]. Dust particles in air can also self-generate charge, and the passage of Saharan dust and Iberian smoke carried aloft over the UK was detected by a change in PG measured in Reading, Chilbolton and in Bristol [6], and charged dust overhead has been detected using arrays of field mills in Portugal [27]. Both examples demonstrate the advantage of using more than one PG measurement site.

Urban measurements of PG using a Bendorf electrograph were taken in Portela, Lisbon, Portugal, which were analysed by Silva et al [17]. These were separated by fair weather and all weather and were characterised by a combination of anthropogenic and planetary cycles that contribute to the diurnal cycle, and also the purely anthropogenic weekly cycle. Weekdays showed a greater span of values than weekends, which indicated the effect of aerosol resistive loading of the atmosphere when traffic levels are higher. Lomb-Scargle periodograms indicated weekly, daily and half-daily cycles.

Subsequent analysis of the PG data set from Portela have shown correlation with aerosol due to the direct relationship between aerosol concentration and air conductivity [1], and a relationship between PG and pollutant gas concentrations, as both measurements are correlated with aerosol concentration [2].

A morning peak in the averaged diurnal cycle of the atmospheric PG was observed at a site in Israel [28] which was postulated to be due to a peak in aerosol concentration as a result of ground heating related uplift on aerosols. Atmospheric electrical measurements have been used to measure micro-meteorological features, for example Anisimov et al [29] used an array of electrical field mills in a site with low pollution levels to record the atmospheric PG at a sampling rate of 10 Hz. This approach delivered new insights in the turbulent transport of charge carriers (ions and charged aerosols) in the measurement location. A sunrise effect on artificially produced ions has been observed near high voltage power lines [30], where an increase in variability of PG measured by a field mill was shown to exist after sunrise; and a build-up of negative space charge overnight, which then dissipates after sunrise, was shown in PG measurements at a sub-urban UK Met Office site [5].

2. Materials and Methods

2.1 Site descriptions

Three different sites were chosen as monitoring locations for the atmospheric PG and local meteorology. Two were chosen in the City of Bristol, UK, and one in a rural location at Langford, North Somerset, UK. Pollutants, in particular aerosols, would be expected to be higher at the two urban sites, and any anthropogenic signal should be more apparent in these than the rural Langford site. The urban sites were both on rooftops, one at the University of Bristol's School of Chemistry (SoC) and the other at the then-called at-Bristol Science Centre (AtB, since renamed We the Curious). The rural site is located 17 km away from the Bristol sites within the apiary of the University of Bristol's School of Veterinary Science in Langford (LVS). The two Bristol sites are 0.8 km apart (figure 1).

Figure 1: (a) map of England and Wales (b) Bristol and surrounding counties and (c) Bristol city centre showing the location of the two Bristol sites and the Langford site. Image credit: Google Earth, 08/08/2018.

2.2 Instrumentation

The atmospheric electric field can be measured using an electric field mill, which contains a rotating vane that induces a current alternately when the sensing vane is covered by a grounded vane, then uncovered and exposed to the atmospheric PG. The at-Bristol and Langford sites use a JCI 131F high frequency electric field mill, while the School of Chemistry roof site uses a JCI 131 field mill with a lower frequency response. The At-Bristol and Langford sites record at 10 Hz, which for this analysis was averaged to 1 s and 1 minute samples, the School of Chemistry site recorded samples at 1 s, also averaged to 1 minute. Local weather was recorded at 1 s by a Gill Maximet 501 integrated weather station measuring wind speed and direction, solar radiation, temperature, pressure and humidity and a Gill Maximet GMX100 to indicate rainfall at the Langford and at-Bristol sites. The GMX100 is a 0.08 mm resolution optical rain gauge, detecting the size and number of rain drops falling onto a glass dome and converting this to rainfall intensity (http://gillinstruments.com/products/anemometer/maximet-compact-weather-stations.html). The School of Chemistry site used a Gill Maximet GMX500 measuring wind speed and direction, temperature, humidity and pressure, and also contained occasional aerosol measurements using a TSI 3010 Condensation Particle Counter.

2.3 Instrument locations

The field mill and weather stations on the University of Bristol rooftop were placed on a 1.5 m stand, the roof was 30 m from the ground on the South side and 22 m from the ground on the North side, as the building is on a hill. The rooftop location is shielded by a larger building and smaller buildings surrounding the measurement location, and therefore the weather conditions measured at this site are locally affected by the surroundings, in particular the wind speed which is affected by street channelling and cannot be assumed to be representative of the weather conditions in Bristol as a whole. The instruments on top of the at-Bristol science centre were mounted on 2 m poles on the building edge, but unlike the Bristol University site, they are not sheltered by other buildings. The building height is 15 m above ground near the harbourside, in a low lying part of Bristol. The Langford Apiary site is not a rooftop site, but in a small fenced area, the instruments are mounted on two separate 2 m stands near to some bee hives. A large tree does exist ~5 m from the field mill which may affect the overall value of atmosphere PG to an extent that may be seasonal, and the instruments were close to some wind shields erected to protect the beehives nearby, but the wind shields were shorter in height than the field mill and weather stations. These positions are summarised in table 1.

Table 1: Instrument locations

Site	Building Height	Instrument Height	Latitude	Longitude
SoC	26 m	1.5 m	51.4570 deg	-2.6000 deg
AtB	15 m	2 m	51.4506 deg	-2.6008 deg
LVS	NA	2 m	51.3467 deg	-2.7798 deg

2.4 Field calculations

An electric field mill on a conducting pole can act as a potential probe, but will enhance the field due to its own geometry. The field measured at the instrument surface (E_f) is affected as a function of the field mills effective diameter, *d*, and the height above ground *h*. The calculation to estimate the atmospheric PG at the field mill sites is given in Eq. (1) [31].

$$PG = E_f \, d \, / \, h \qquad (1)$$

The three sites chosen for these instruments are not ideal sites for absolute values of PG as building geometries and other conducting structures can distort the field enhancing the PG at the measurement point. However, the enhancement is a function of the geometry and, if the geometry of the site does not change, then a simple form factor can provide a corrected value of PG as if the measurement were taken on a flat plain, but for the current study, corrected values were not used.

2.5 Limitations of the data set

There are two limitations to the work presented here that could not be overcome in the current study. First, the data set is not be long enough for conclusions to be drawn on seasonal or annual effects, and second the data is presented as actual field values and not corrected for the presence of buildings and height above ground. It was not possible to collect more data from all three sites running simultaneously (equipment availability) and therefore the comparison of sites, which was an aim of the study, can only be undertaken with the data available. The data set does allow subsets of the data to be analysed to investigate specific questions regarding aerosol content and meteorology.

It was also not possible to make measurements using, for instance, a passive wire antenna or calibrated field mill, on a nearby flat area of ground to measure the effects of building distortion due to the malfunction of two of the three field mills in the study. While corrected values would be required if these data were used to estimate charges overhead in clouds, for example, the shape of the time series is enough to discern much about ion-aerosol interactions, and other factors affecting ground-based measurements of PG in urban and rural settings. Comparison of the shape of the time series and distributions of the measured fields enable differences in weather effects and aerosol loading to be investigated.

3. Results

3.1 Time series of whole data set

The data collected at all three sites are represented as time series in figure 2, showing the largest variations of PG present in disturbed weather. To concentrate on fair weather fields, any data during and 60 minutes before the onset and after the finish of rain as measured on the GMX100 were removed. The SoC site did not have an instrument to measure rain and so used the same measurement as AtB. The resulting time series is shown in figure 3 and shows a much more stable field, with the rain removed, though some periods of disturbed PG remain implying that rainfall alone is not enough of an indication of fair weather fields.

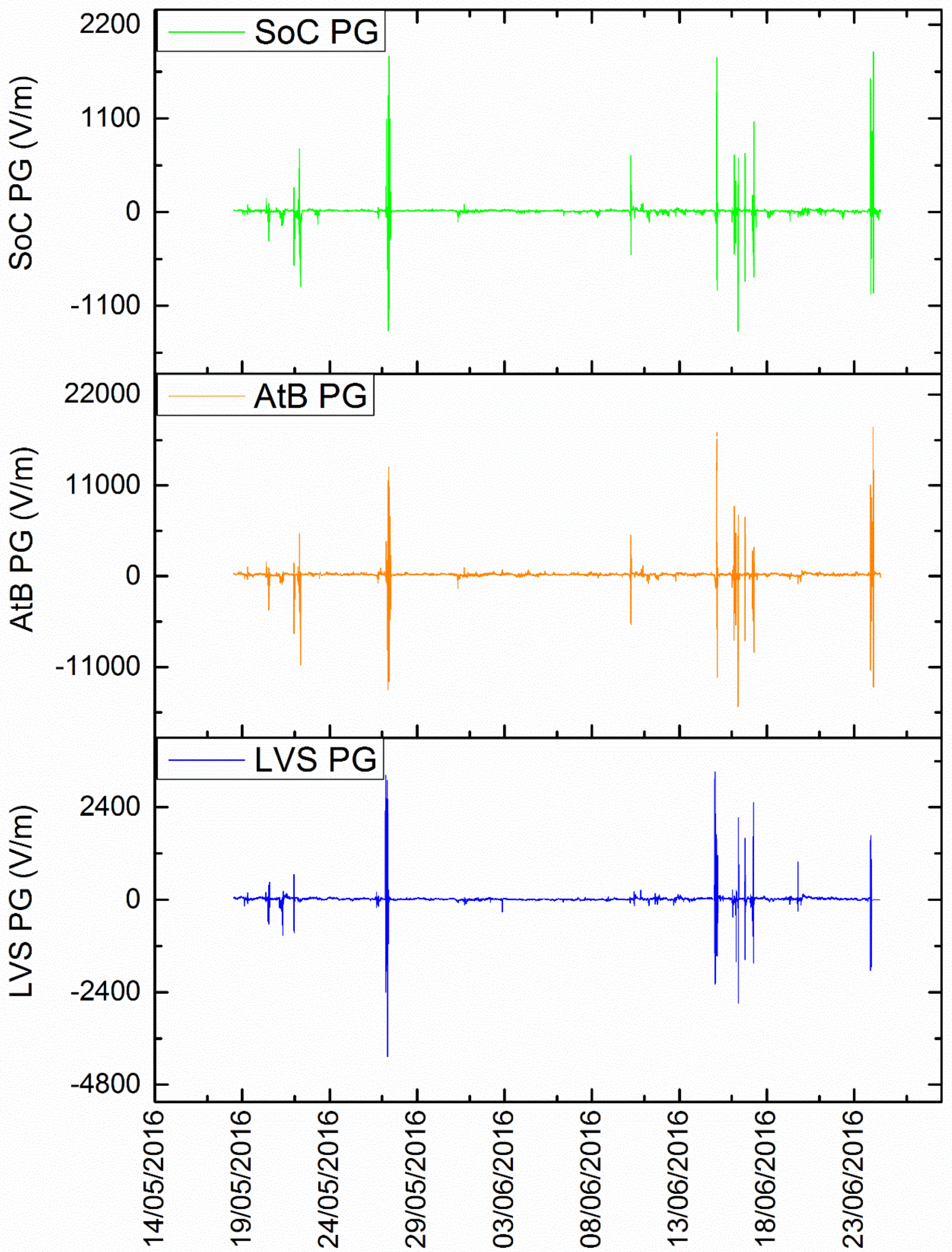

Figure 2: Time series of atmospheric PG measured at the Langford Vet School rural site (LVS, blue), the At-Bristol Science Museum (AtB, orange) and the School of Chemistry in Bristol (SoC, green).

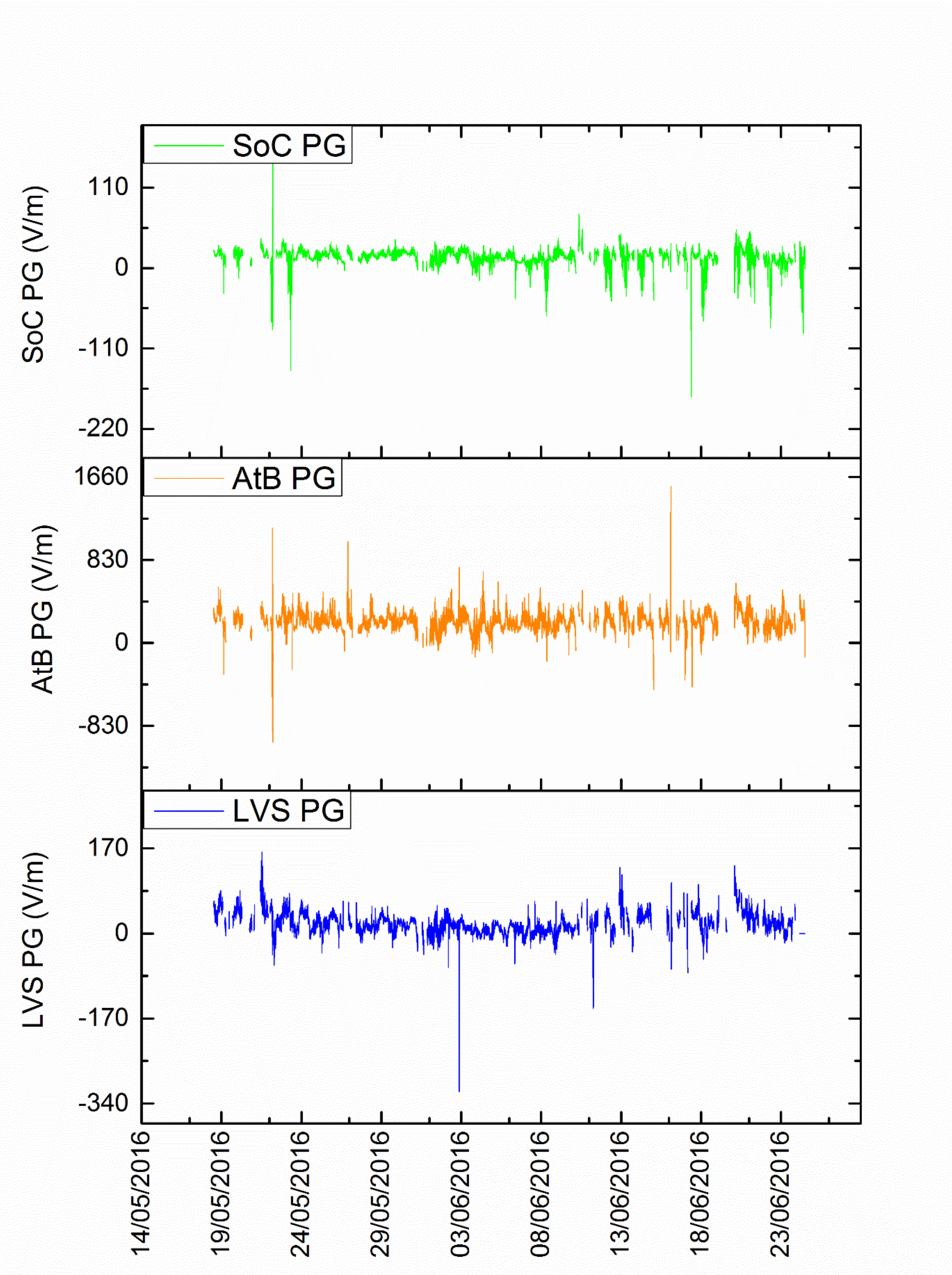

Figure 3: Time series of atmospheric PG measured at the Langford Vet School rural site (LVS, blue), the At-Bristol Science Museum (AtB, orange) and the School of Chemistry in Bristol (SoC, green) with data removed during and for one hour before and after rainfall.

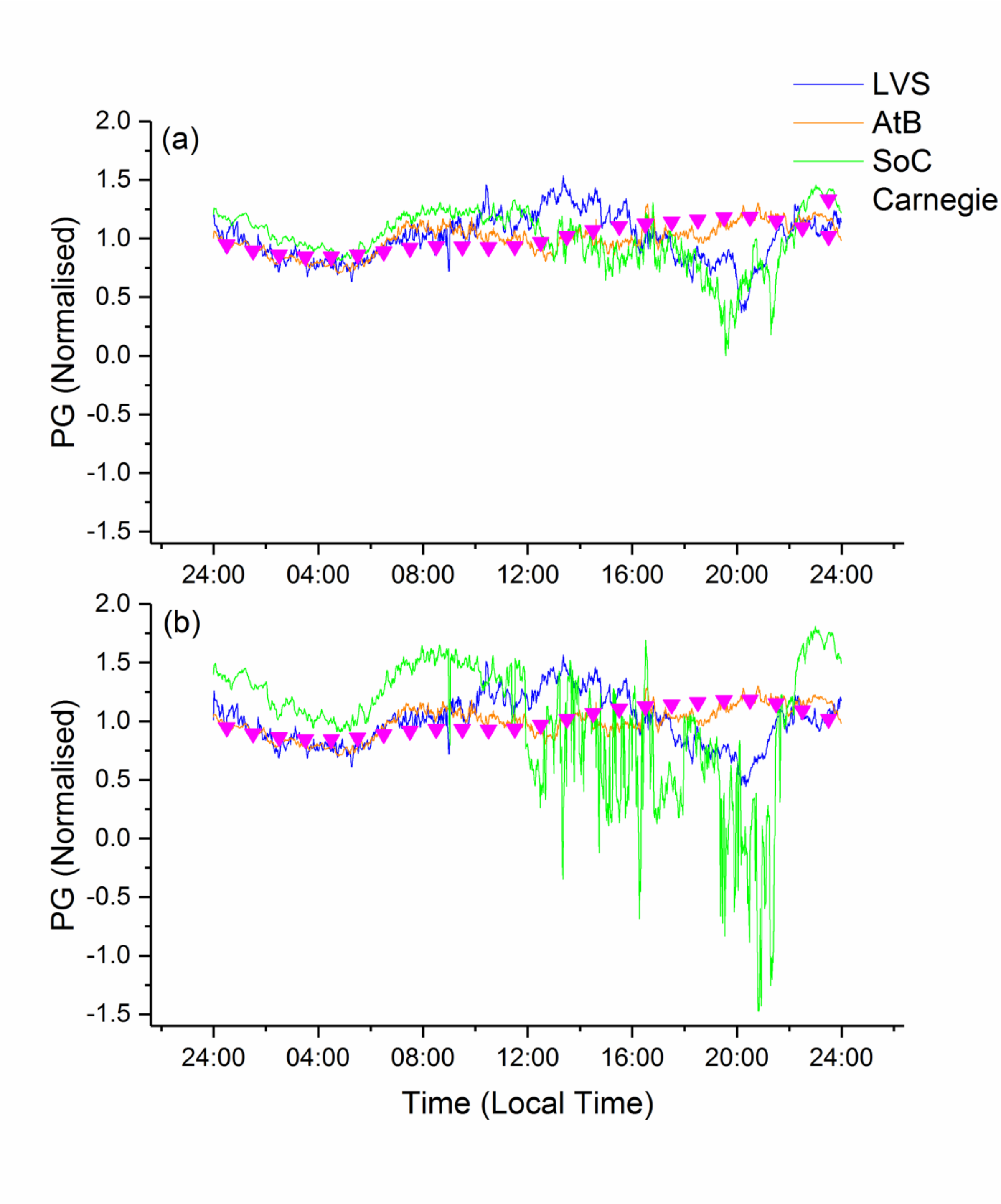

Figure 4: Averaged daily cycle (a) when rain is removed one hour before, after and during rainfall, and (b) with five days of extreme fields also removed. Carnegie curve data reproduced from [12].

The daily average curve was calculated from the data set with the rain removed and are plotted against the Carnegie curve [12] (local time) in figure 4(a), normalised to their own mean. We might expect the urban fields to show peaks at rush hour to correspond to the increased aerosol concentration, and there may be peaks at 8 am and 5 pm (local time) in the AtB trace, but, no such peak was evident at the SoC site. It is also notable that the three sites correlate best to each other and to the Carnegie curve overnight when conditions are calmer on average and aerosol concentrations within the city are lower. However, the large variations in field at the LVS and SoC sites in the afternoon are sufficient to mask any aerosol loading effect. Removal of five days of data that show large extremes of PG due to disturbed weather (22/05/2016, 23/05/2016, 03/06/2016, 16/06/2016, 17/06/2016) increases the variability of the normalised data at the SoC site (figure 4(b)) comparatively to the other data sets, as that variability is now larger in comparison to the baseline. As this is the only site where rain incidence is not recorded in the same location, it may be due to local variation in rainfall, but large differences in weather conditions over neighbourhood scales is unlikely. It may also be the case that the relative increase in PG at AtB relative to LVS and SoC between 16 and 22 hours could be due to local aerosol loading at the urban site given its close proximity to a busy road.

To show the variation with each day, figure 5 shows boxplots for every day within the study site for the two sites (AtB and LVS). They represent the 95th, 75th, 50th, 25th and 5th percentiles of the PG within that day and show the great variability within days and day to day that can be present. The most electrically disturbed days are shown by the highest spread of values in both sites. If data are removed one hour before and after recorded rainfall, the box plots show less extreme values (figure 6) and allow for better comparison between the two sites, but highly variable days are still evident.

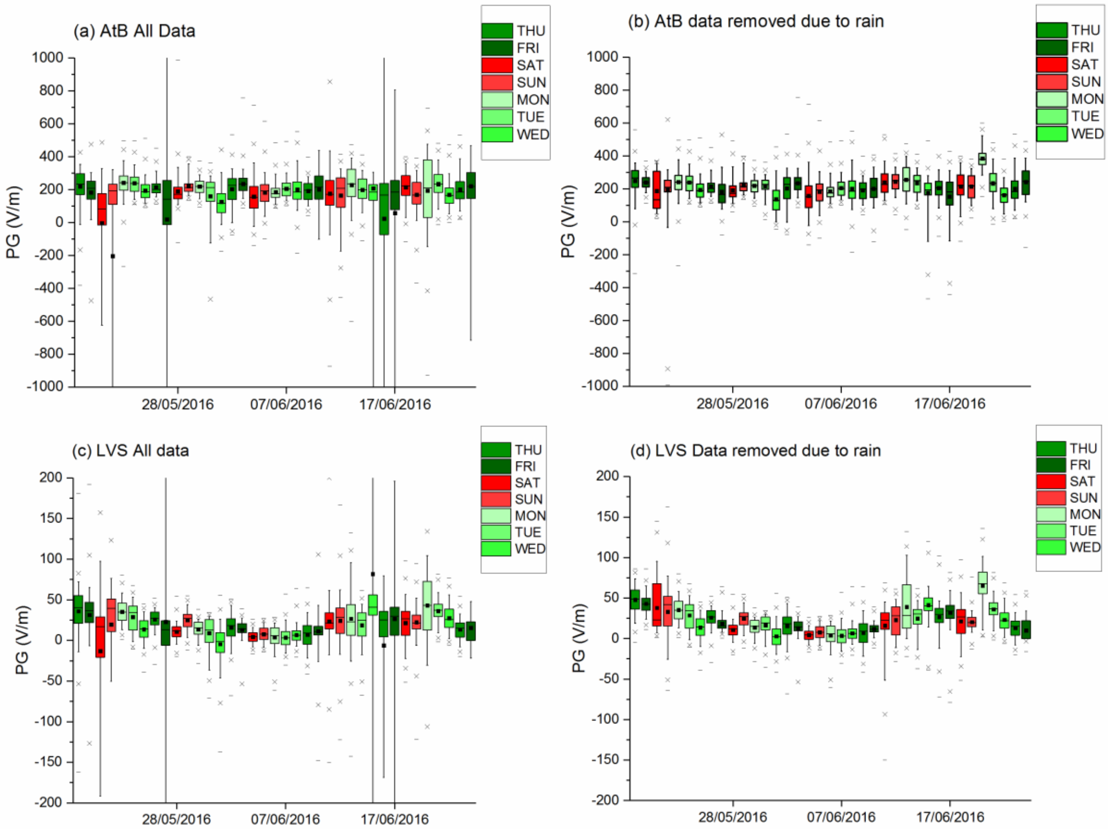

Figure 5: Box and whisker plots of (a) the AtB site in Bristol with all data and (b) data removed one hour before, after and during rainfall and (c) the LVS site with all data and (d) data removed one hour before, after and during rainfall. Boxplots show 95th, 75th, 50th, 25th and 5th percentiles of PG values in each day.

Scatter plots of both the mean and the interquartile range of the daily PG values were made to test similarities in the urban and rural sites. Correlations were tested using a Pearson correlation one tailed test. The daily median had a Pearson correlation coefficient r = 0.36 with all data, but r = 0.68 when rain data was removed, while conversely the interquartile range was better correlated with all data (r = 0.76) than when rain data was removed (r = 0.23). The better correlation in daily median when rain data is removed suggests that global background fields do have a degree of similarity with the two sites, but that this is masked in disturbed weather, whereas the greater correlation in interquartile range when disturbed weather is included shows that the most disturbed weather affects both sites at the same day.

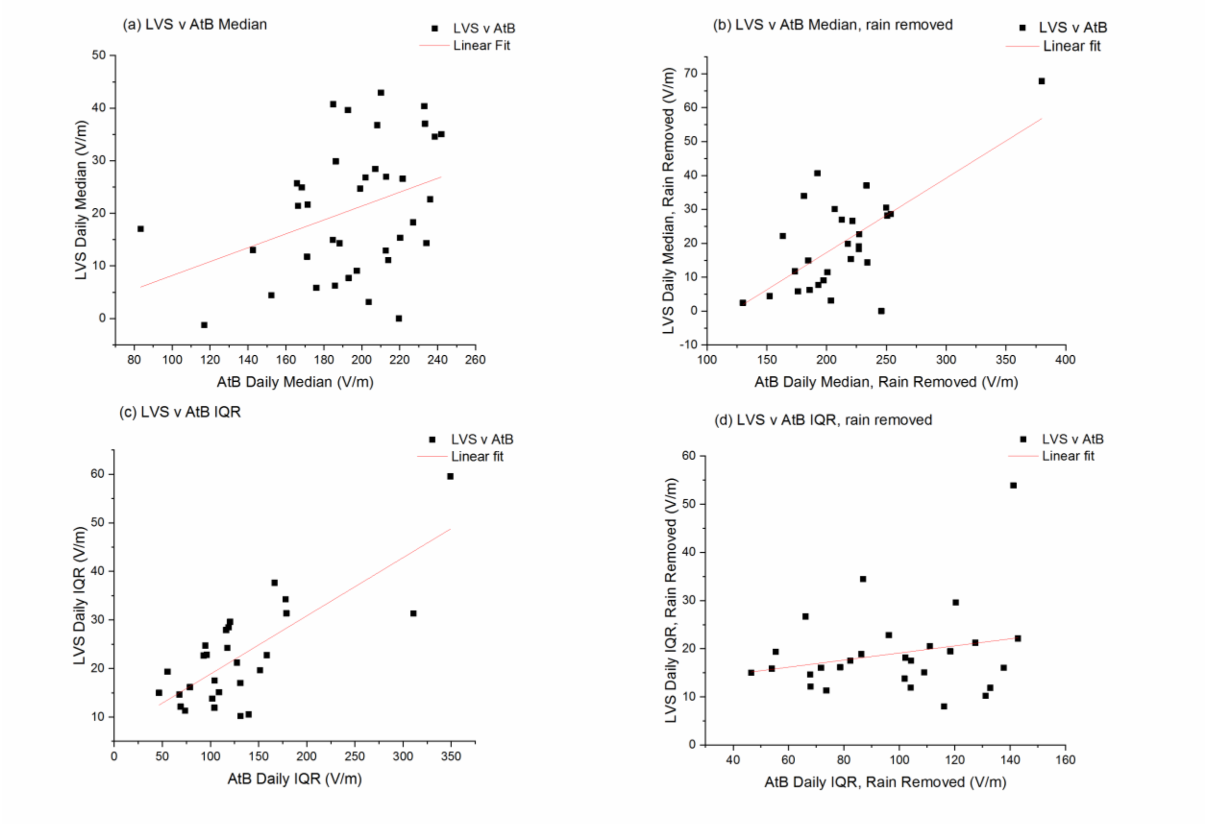

Figure 6: Scatter plots comparing (a) daily PG median and (b) interquartile range values between the rural LVS site and the urban AtB site for all values, and for (c) median and (d) interquartile range with data removed during and one hour before and after rainfall.

An attempt to average each day to ascertain whether weekends and weekdays were noticeably different did not show any clear weekend / weekday difference (figure 7), the highest and most variable values were on Monday, in both sites. This may be due to the disturbed weather on the 20th June having an undue influence, and so therefore there is not enough statistical power in this dataset to see any predicted weekend / weekday differences caused by higher levels of aerosol present as meteorological events mask any potential effect. The size of the data set is not sufficient not investigate seasonal effects or long term trends within the data series, but the series includes 37 days of data from three unique sites in a variety of weather conditions, including some extreme weather events. Examples of high and low aerosol days, and of disturbed weather events can be investigated to demonstrate the effect of aerosol in urban measurements, and the distance scale of atmospheric PG changes.

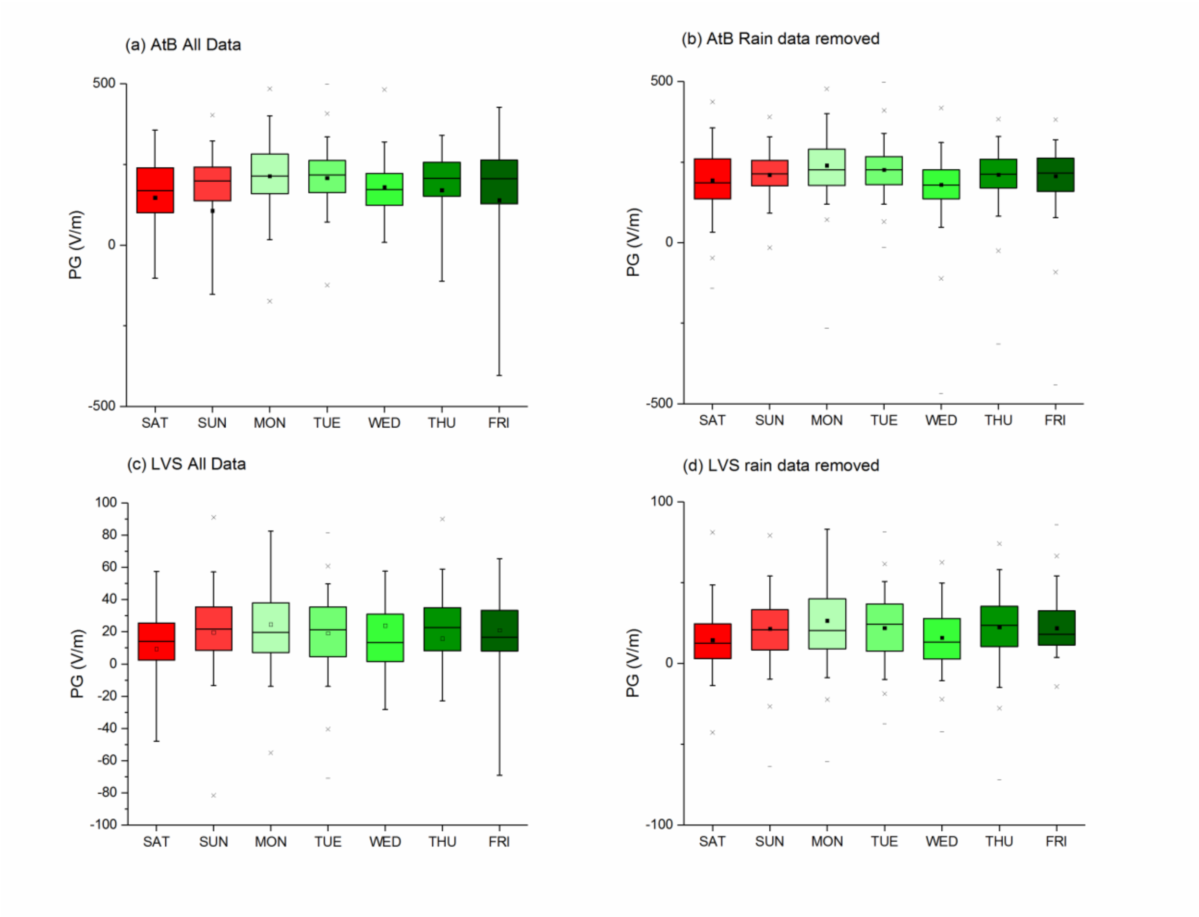

Figure 7: Box plots for PG values for all data separated by day of the week, showing 95th, 75th, 50th, 25th and 5th percentiles of PG values in the rural LVS site and the urban AtB site for all values, data removed during and one hour before and after rainfall.

3.2 *Fair weather effects of aerosol*

PG levels are known to be affected by aerosol concentrations by increasing the resistivity of the air, to test whether this effect shows a difference in aerosol levels that could be present at weekends and weekdays, a histogram was created of the 1 minute averages of PG in both the urban AtB site and the rural LVS site separated by weekend and weekday (data discarded during and 60 minutes before and after rain).

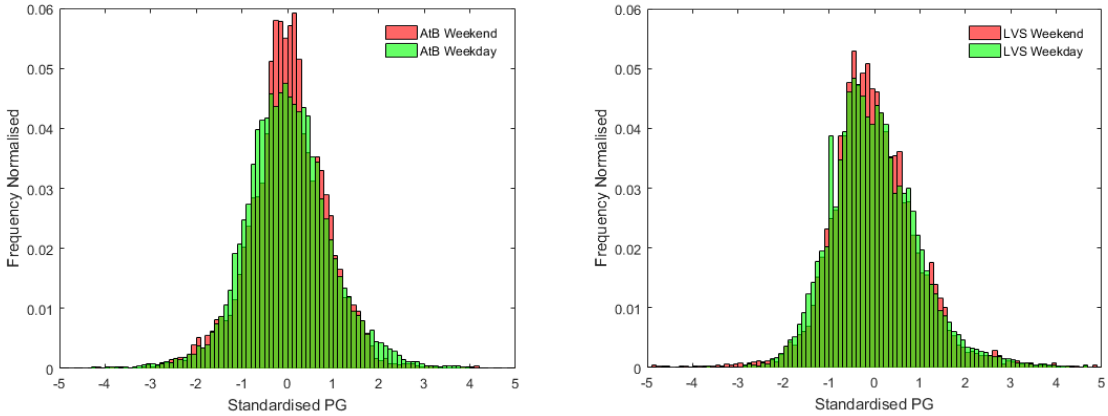

Figure 8: Normalised histograms of the weekday (green) and weekend (red) PG measurements for the LVS rural site and AtB urban site with data removed during and one hour before and after rainfall.

All plots exhibit a normal distribution. There is a visual difference in histogram shape in the histograms at AtB, with a narrower distribution during the weekend (when aerosol content would be lower). However, Kolmogorov-Smirnof tests were run, and no statistical difference was found between the distributions of weekend and weekday distributions of PG ($p < 0.01$ for both LVS and AtB sites).

Lomb-Scargle periodograms allow the frequency spectrum to be calculated in interrupted data sets by estimating the frequency spectrum from a least-squares fit of the sinusoids [32, 33]. The urban AtB site and the rural LVS site were compared. Weekends at an urban site have lower traffic and therefore lower air pollution, consequently a weekly 7-day cycle may be evident in the AtB site, but not in the LVS site, whereas the 24 cycle is seen in both sites (Figure 9), but a larger data set would be required to have any confidence in a seven day cycle. There is a clear half day cycle evident in the AtB site which would account for the double diurnal traffic signal, rather than the single daily cycle that the Carnegie curve shows.

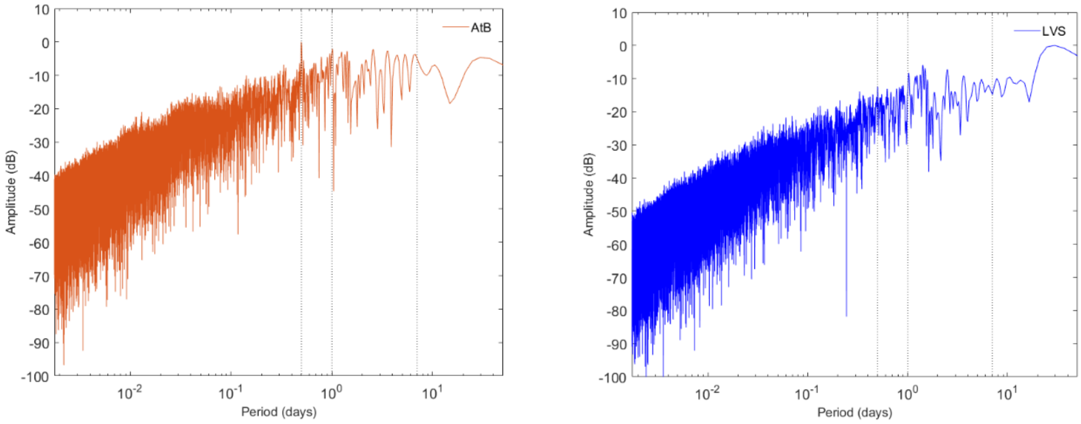

Figure 9: Lomb Scargle periodograms of 1 minute average PG measured at the AtB urban and LVS rural sites, dashed vertical lines represent a half-day, full-day and weekly cycle.

Given that aerosol content has been shown to have an effect on atmospheric PG in previous studies, the correlation between PG at the two Bristol sites was investigated on a weekday chosen with high aerosol content and a public holiday with low aerosol content measured at the SoC site using a TSI 3010 CPC. Figure 10 shows that the correlations between the two sites are similar on both the high and low aerosol days, with good correlation in the Bristol sites and poor correlation with the Bristol and Langford sites; a Pearson correlation coefficient R = 0.76 and R = 0.77 between AtB and SoC on the high and low aerosol days respectively, and R = 0.31 and R = 0.09 between AtB and LVS ($p > 0.99$).

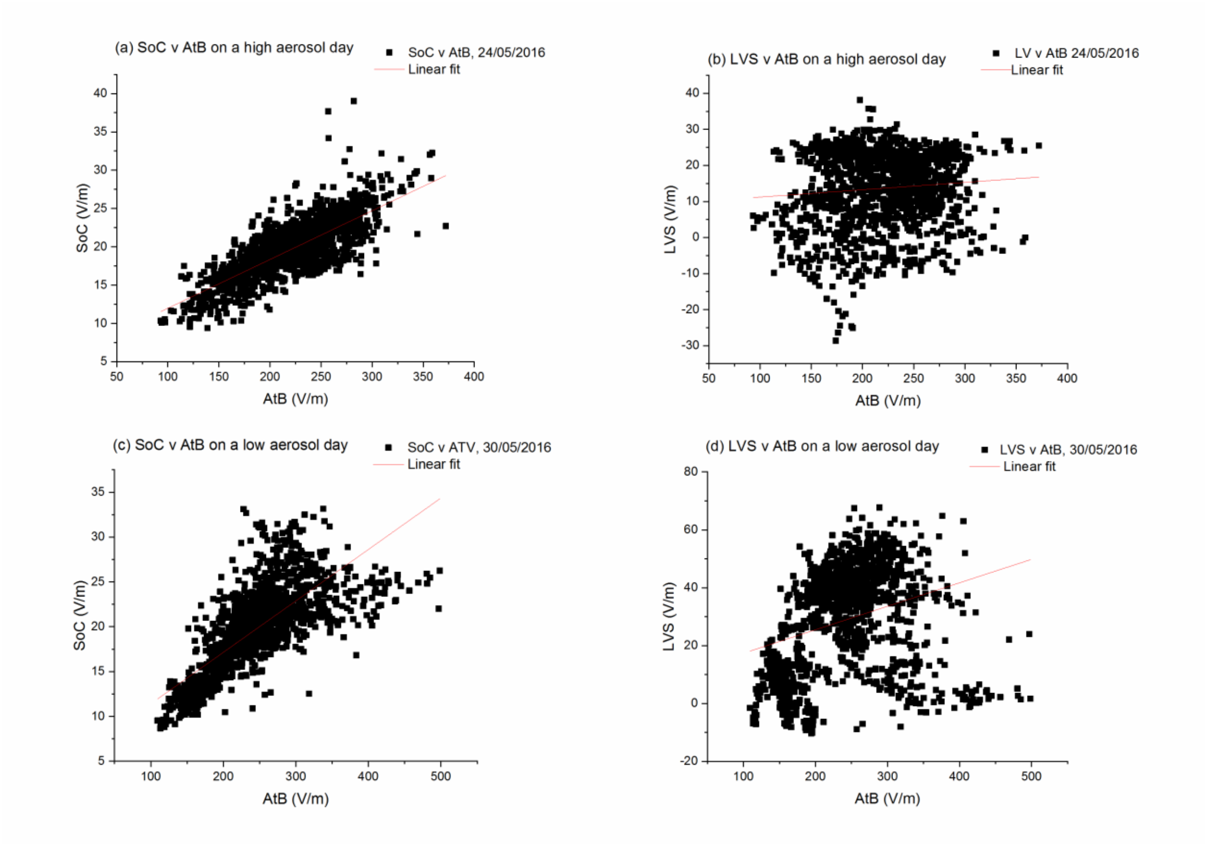

Figure 10: Correlations between (a) the AtB and SoC site and (b) the SoC and LVS site on 24/05/2016, a day with high aerosol content and between (c) the AtB and SoC site and (d) the SoC and LVS site on 30/05/2016, a day with low aerosol content)

3.3 Distance scale of disturbed weather effects

While the fair-weather fields could show the effect of traffic in an urban environment, any aerosol related local effects can be masked by the large changes in field shown by disturbed weather. One example of a disturbed weather day is presented here. A storm passed both Langford and Bristol on the 27th May 2016 exhibiting typical field inversions and large field values as indicated in the box plot in figure 5.

Figure 11 shows the field values for a 6 hour extract at the three sites, there were storms travelling from the South East, and the storm is shown passing Langford at 18:00 and Bristol at 19:30. The alternating polarity reversals is characteristic of multicellular convection, with a good agreement between both Bristol sites showing that the storm affects PG values over a city scale.

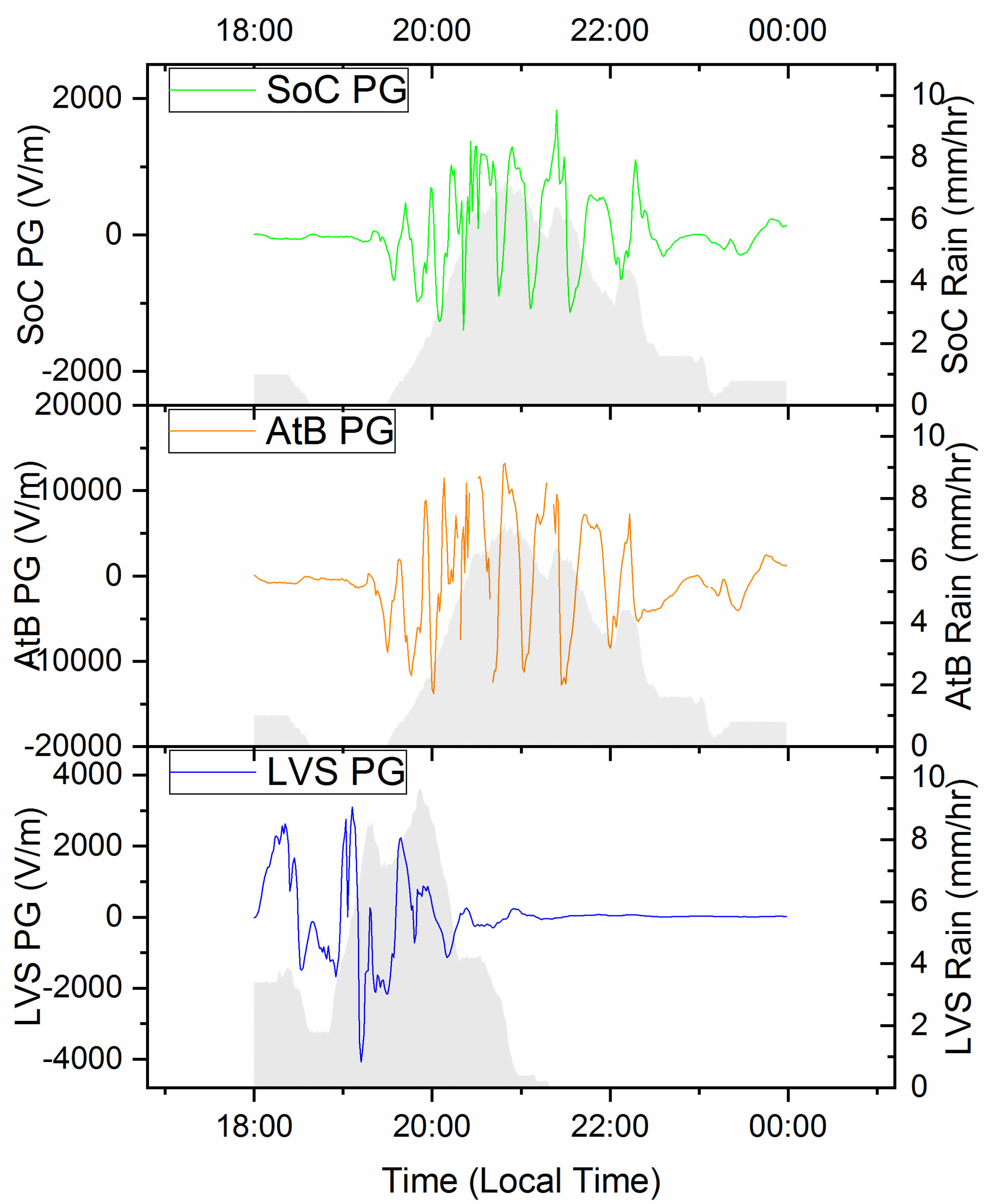

Figure 11: The passage of a storm showing disturbed weather at the (a) AtB, (b) SoC and (c) LVS sites. Shaded grey profile graphs show rainfall recording.

4. Conclusions

The measurements from these three sites show consistency with previous findings on anthropogenic aerosol related effects on PG, and in the extent to which disturbed weather affects local PG measurements. It has also allowed new insights into the length scales to which these effects occur, and has shown the use of precipitation alone as an indicator of electrically disturbed weather to be inadequate.

Having two PG measurements within a city allowed an opportunity to test whether increased aerosol concentration within a city would increase localised effects on PG by reducing the correlation between both sites. Selecting a high and low aerosol concentration day and comparing the Pearson correlation provided a first test, but no difference was found. During disturbed weather, the field inversions caused by charge carriers overhead were temporally similar in both urban sites, but different in the rural site several km away. These first tests have shown that the PG fluctuations measured at one roof top site in the city can be assumed to represent that of the surrounding 1 km, though absolute values will be affected by local geometry. The example of a thundercloud passing overhead showing similar fields at the two urban sites shows that this similarity holds in disturbed weather. Further tests should look at street level and roadside measurements to measure whether newly generated charges and particles from vehicles provide greater local distortions to the global field.

It is well known that rain and storm clouds cause large disturbances in the atmospheric PG, which is why researchers interested in global properties of the atmospheric electric field will often remove disturbed weather. While a general consensus on how to establish what is 'fair weather' has not yet been reached, it is usually assumed to mean clear skies with no precipitation and low wind speeds, though recent efforts have been made towards a standardised definition that include the removal of very low (< 1 ms^{-1}) wind speeds, and a more robust criteria on cloud cover [13]. In the present study, cloud cover was not measured and cannot be used to identify disturbed weather. While removing data one hour either side of rain removed most disturbed weather, large fluctuations of field on stormy days still persisted, and so rain measurements alone are not sufficient to identify fair weather.

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